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DETERMINATION OF THUNDERSTORM DENSITY BY RADIO OBSERVATIONS FROM A SATELLITE

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PREPARED FOR:
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The RAND Corporation
SANTA MONICA • CALIFORNIA

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PREFACE

This report discusses the types of satellite observations at radio frequencies that might be used to estimate the density of thunderstorms over the surface of the earth. The object of the report is to consider theoretically the possible usefulness of such observations rather than to survey the ones that have already been made or to outline the details of an optimum system for making further observations.

In particular, a method is described for estimating thunderstorm densities that does not require a directional antenna on the satellite or a knowledge of the orientation of the satellite relative to the earth. In this method, the field of view of the satellite is limited by the properties of the ionosphere itself, with the result that the satellite system should be a relatively simple one.

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SUMMARY

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This Memorandum presents a theoretical consideration of the radio frequencies that might be used to estimate the density of thunderstorms from an artificial satellite. The ways that electromagnetic radiation from lightning strokes is propagated through the ionosphere are examined, and a comparison of signal-to-noise ratios at the satellite's receiver is made for the various usable frequencies.

It is found that, above 400 Mc, signal power from a lightning stroke will usually be inadequate, but that at about 300 Mc, with antenna gain of about 10, the signal will probably satisfactorily exceed the noise. In the 6 to 20 Mc range the signal will be well above the noise, and a directional antenna will not be needed because the ionosphere itself can be used to restrict the field of view. At much lower frequencies whistlers are detectable by a satellite receiver, but the location of the source lightning stroke would be ambiguous, and the size of the antenna needed to resolve this ambiguity would be prohibitive.

AUTHOR

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I. INTRODUCTION

Recently several satellites have been made available for meteorological purposes, primarily for infrared and optical observations. The availability of these satellites raises the question as to whether or not there are other types of meteorological observations which might profitably be made from a satellite. In particular, it seems possible that some useful data could be obtained from measurements at radio frequencies.

Since the present satellites weigh only a few hundred pounds and since future satellites will probably carry at least some of the equipment that is carried at present, it seems reasonable to restrict a preliminary discussion such as this one to measurements that might be made with equipment weighing a hundred pounds or less. Measurements such as radar observations of the sea, clouds, or ionosphere, which require a transmitter and a moderately large power source, do not seem to be of immediate interest because of the weight of the equipment that must be carried, although they may ultimately be important. Of greater immediate interest are passive measurements that can be made with only a receiver and antenna, and that will add less weight to the satellite.

There are several different sources of signals that might be detected by a receiver in a satellite. First, there are man-made signals received from transmitters on the earth. Some of these may cause unpredictable interference, so that measurements may have to be confined to relatively unused frequency bands, and it may be desirable to use narrow-band receivers to avoid the interfering signals. Second, there is noise of solar and cosmic origin that is not directly related to meteorology and will thus be only a source of interference in meteorological measurements. Third, anything that absorbs electromagnetic energy at a particular frequency will also radiate thermal noise at that frequency. For example, the oxygen and water vapor in the atmosphere will emit radio noise in the vicinity of their absorption bands. This noise will be mostly at frequencies above ten-thousand megacycles. Fourth, lightning flashes in thunderstorms produce strong pulses of electromagnetic energy at radio frequencies, usually referred to as atmospheric noise. The number of these pulses received by a satellite would give an indication of thunderstorm activity in the area below the satellite, which might be useful meteorological information. It is the object of this document to investigate the possibility of measuring thunderstorm activity by observing such radio-frequency signals from a satellite.

II. THE SIGNAL RECEIVED BY THE SATELLITE

To estimate the strength of the signal that will be received by a satellite from a lightning discharge, both the strength of the source and the effect of the path of propagation on the signal must be considered. The characteristics of the source have been summarized by Watt and Maxwell.[(1)] Lightning discharges usually start with a weakly ionized pilot streamer that travels from the charged cloud toward the ground in spurts lasting roughly 100 microseconds each. Each spurt is followed by a highly ionized leader, which lasts about a microsecond. This process continues until the leader reaches the ground. The time during which this process occurs is called the predischarge period and is of the order of a millisecond in duration. When the leader reaches the ground the main stroke returns upward, producing the main pulse of radiated energy.

The pulse radiated by the main stroke has no sharp discontinuities, and the amplitude of its frequency spectrum varies inversely with the square of the frequency at sufficiently high frequencies. The smaller radiated pulses produced during the predischarge period have more pronounced discontinuities, and hence the field they produce has a frequency spectrum that varies inversely with the frequency. Thus even though the field associated with the main stroke is stronger than that associated with the predischarge period, there is a frequency above which the amplitude of the spectrum of the predischarge period is greater than that of the main stroke. This frequency is roughly 20 kc. Frequencies in the range of 20 kc and below will not normally penetrate the ionosphere, so that a satellite that flies at an altitude of four or five hundred miles, which is generally above the region of maximum electron density in the ionosphere, will not detect these frequencies (except possibly as a result of whistler-mode propagation, which will be discussed later). It follows that the signals received from thunderstorms by a satellite will come predominantly from the predischarge period of a lightning flash, and the effective frequency spectrum of the source of these signals will be one in which the field strength is inversely proportional to the frequency. The amplitude of the radiated component of this spectrum for a typical lightning flash is estimated by Watt and Maxwell to be about 1/2 volt/meter at a frequency of 100 kc as detected by a receiver with a bandwidth of 1 kc at a distance of 1 mile from the source. This amplitude can be determined under other conditions from the fact that it varies inversely with the distance from the source and is proportional to the square root of the bandwidth of the receiver. The analysis of Watt and Maxwell is not extended to frequencies above 100 kc, but the measured variation with frequency of atmospheric noise intensities at night, when ionospheric absorption is low, suggests that the spectrum described above is correct to the highest frequencies that can be propagated by sky-wave transmission, and can be reasonably assumed to be roughly correct at all frequencies of interest. (See, for example, Ref. 2, p. 159 for atmospheric noise data.) Such direct data as is available on the spectrum of radiation from a single lightning stroke is at least not in strong disagreement with this assumption. (See Ref. 3, p. 22.)

It remains to estimate the propagation factors that may influence the signals along the path to the satellite. At frequencies below 10,000 Mc, the constituents of the atmosphere usually give very little absorption, and the gradients of dielectric constant are not great enough to give appreciable deflection of the signal except for signals that are almost tangential to the earth. Thus, for signals that make an appreciable angle with the horizontal, as will many of those seen by a satellite, the effects of the earth's atmosphere can be ignored, and we need only consider ionospheric effects.

The ionosphere may produce both absorption and deflection of the electromagnetic pulse. Absorption in the ionosphere occurs largely in the D-region. This is the lowest region of the ionosphere and is the one in which the gas density is greatest, and hence the rate of collision of an electron with gas particles is also the greatest. These collisions absorb energy from the electromagnetic field and attenuate the wave. Ionization in the D-region is produced by direct solar radiation and is almost nonexistent at night. Thus appreciable absorption occurs only during the daytime. No signal whose frequency is below the critical frequency of the F2 layer will pass through the ionosphere. During the daytime, when there is appreciable absorption, this critical frequency varies from about 4 Mc to 10 or 11 Mc in tropical regions and is seldom less than 2 Mc even in the polar regions. At these frequencies absorption is generally less than 10 db and is usually much less than this and can be neglected. Thus it is reasonable to assume that absorption is negligible for almost any signal that will reach the satellite, and it is only necessary to determine whether the signal will penetrate the ionosphere or will be reflected by it.

It is usually possible to determine whether a signal can be detected by a satellite without regard for the magnetic field existing in the ionosphere. A signal incident vertically on the ionosphere in the presence of a magnetic field may be reflected at one of three different altitudes, corresponding to three different values of the electron density. The middle one of these three levels is the one at which the electron density is such that the plasma frequency equals the signal frequency, which is the level at which reflection would have occurred if there had been no magnetic field. Of the other two levels, the lower one usually reflects much more of the signal than does the upper one. Thus as the signal frequency is increased, the heights of these three levels of the ionosphere also increase, and the part of the signal that is reflected at the upper level will be the first to pass through the ionosphere entirely but will usually carry little or no energy through the ionosphere. Appreciable signal energy will be transmitted through the ionosphere only when the frequency is high enough that the part of the signal that is reflected by the middle of the three levels can pass completely through the ionosphere. This occurs at the same frequency at which signal energy would have penetrated the ionosphere if there had been no magnetic field. To this extent, the ability of the ionosphere to transmit the signal to the satellite is the same as if no magnetic field existed, and the detectability of the signal can be determined from the usı l data for predicting sky-wave propagation, ignoring the effect of the magnetic field of the earth.

If the effect of the magnetic field of the earth is neglected, the effective refractive index of the ionosphere is

$$\mu = \sqrt{1 - \frac{f_p^2}{f^2}} \quad ,$$

where f is the frequency of the signal and f_p is the plasma frequency, which depends only on the local electron density. If the earth is assumed to be flat, and the electron density in the ionosphere is assumed to depend only on the altitude, and if φ is the angle between the direction of propagation of a wave and the vertical as shown in Fig. 1, Snell's law says that $\mu \sin \varphi$ is the same at all points along the wave as it passes through the ionosphere.

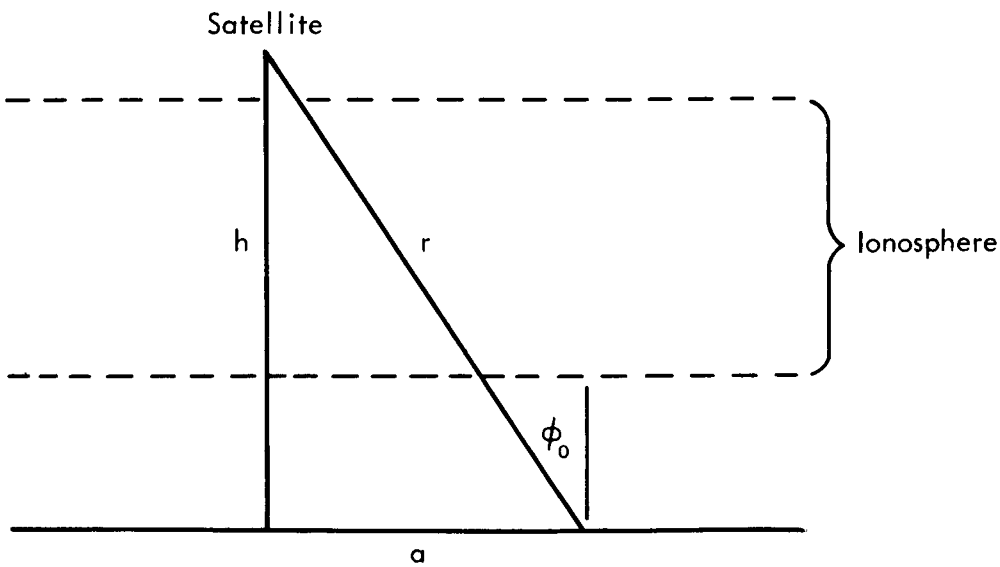

Fig. 1 Diagram of electromagnetic ray penetrating the ionosphere

If we consider a wave starting near the surface of the earth at an angle $\varphi = \varphi_0$ and at a point where $\mu = 1$, then $\mu \sin \varphi = \sin \varphi_0$ all along the path of the wave. The criterion that the wave will penetrate the ionosphere is then that φ is always less than 90°, so that the wave always has an upward component of motion. This is the same as saying that $\sin \varphi < 1$, or $\sin \varphi_0/\mu < 1$. Using the value of μ above, this is equivalent to $\sin \varphi_0 < \sqrt{1 - f_p^2/f^2}$, which implies that f is always greater than $f_p \sec \varphi_0$. The maximum value of f_p normally occurs in the F2 layer and is the critical frequency f_c of that layer for signals vertically incident on the ionosphere. Thus the criterion that the wave will penetrate the ionosphere is that $f > f_c \sec \varphi_0$. The value of f_c can be estimated at different times and locations from data given in Ref. 2. If we denote the height of the satellite by h, and the distance from the source to the satellite by r (Fig. 1), and if the source of the signal is assumed to be essentially on the ground, and the path of the wave is assumed to be nearly a straight line, then $\sec \varphi_0 = r/h$, and the criterion that a signal from a given source reaches the satellite is that $f > f_c\ r/h$. The assumption that the path of the wave is essentially straight is valid if the frequency observed is appreciably greater than $f_c\ r/h$. When the position of the satellite and the time of day are given, f_c can be estimated and h is known. Then for a given observed frequency f, the detectability of the signal, depends only on the distance r from the source to the satellite.

This simple relation between the minimum detectable frequency and the distance to the source suggests that the distance to the thunderstorm can be determined by observing the signal at many different frequencies, determining the lowest frequency at which it is received, and estimating the range from the relation given above. However, if the direction from which the signal is received is not known, the distance to the source does not determine the location of the source and may not be very useful information by itself. A more useful result is that signals observed at one frequency must all come from sources within a circle whose center is directly below the satellite and whose radius can be determined from the above relation, and this fact may be very useful in estimating the density of thunderstorms in the region below the satellite. For example, if the frequency observed in the satellite is 1 1/2 times the estimated critical frequency of the F2 layer, the greatest distance from which signals will be received is 1 1/2 times the altitude of the satellite. Assuming the earth to be flat, the sources of these signals will be in a circle whose radius is about 1.1 times the altitude of the satellite, or about four to five hundred miles for typical orbits. If the measured rate at which signals are received is divided by the area of this circle, the number of noise pulses produced per unit area per unit time can be estimated for the region beneath the satellite.

The accuracy of such an estimate of the density of thunderstorm activity depends on the accuracy with which the critical frequency of the F2 layer can be estimated. An indication of the accuracy of this estimate can be obtained from data used to estimate sky-wave propagation characteristics between two points on the surface of the earth. In this data the maximum usable frequency between the two points is defined to be the frequency at which communication is possible 50% of the time, while the optimum working frequency is defined to be the frequency for which communication is possible 90% of the time. For the F2 layer, which is generally the one of interest in transmitting through the ionosphere, the optimum working frequency is usually taken to be 85% of the maximum usable frequency. This suggests that if f_{cp} is the predicted value of the critical frequency f_c, then the actual value of f_c is less than .85 f_{cp} only 10% of the time. If the distribution of f_c is even roughly symmetrical, then f_c will be greater than 1.15 f_{cp} about 10% of the time also, so f_c will be between .85 f_{cp} and 1.15 f_{cp} about 80% of the time.

The area of the circle of radius a from which thunderstorms are detectable by a satellite is

$$A = \pi a^2 = \pi(r^2-h^2) = \pi \left[\left(h \frac{f}{f_c}\right)^2 - h^2\right] = \pi h^2 \left(\frac{f^2}{f_c^2} - 1\right)$$

for a known critical frequency f_c. If the predicted critical frequency is f_{cp}, then 80% of the time this area will be greater than A_1 and less than A_2, where

$$A_1 = \pi h^2 \left[\left(\frac{f}{1.15\ f_{cp}} \right)^2 - 1 \right] \quad ,$$

and

$$A_2 = \pi h^2 \left[\left(\frac{f}{.85\ f_{cp}} \right)^2 - 1 \right] \quad .$$

If we somewhat arbitrarily determine the estimated density of thunderstorm activity by assuming the signals observed come from an area equal to $\sqrt{A_1 A_2}$, then 80% of the time the estimated density will be in error by a factor lying between $A_1/\sqrt{A_1 A_2}$ (or $\sqrt{A_1/A_2}$) and its reciprocal, which is $A_2/\sqrt{A_1 A_2}$ (or $\sqrt{A_2/A_1}$). The factor of error $\sqrt{A_2/A_1}$ as well as the values of $A_1/\pi h^2$ and $A_2/\pi h^2$ are plotted as functions of f/f_{cp} in Fig. 2. It is seen that the estimated density will be within a factor of about 1.7 of the actual density 80% of the time if the observed frequency is one and a half times the predicted critical frequency. This factor cannot be reduced appreciably by going to higher frequencies. In fact, it approaches the value 1.15/.85, or 1.35, as the frequency increases to infinity. Of course, if the observed frequency is far above the critical frequency the assumption that the earth is flat is no longer reasonable, so this limiting value is only of interest to show that not much more improvement in accuracy can be obtained by increasing the ratio f/f_{cp} to much more than 1.5 or 2 at the most.

Measurements of atmospheric noise suggest that the amount of thunderstorm activity may vary by a factor of a thousand or even ten thousand to one at different points on the surface of the earth. For this reason, a possible error of a factor of about 1.7 in estimating the amount of thunderstorm activity may not be important in some applications. If not, then the satellite may use an antenna of very low directivity and an arbitrary orientation, which makes for a relatively simple design of the satellite system. The

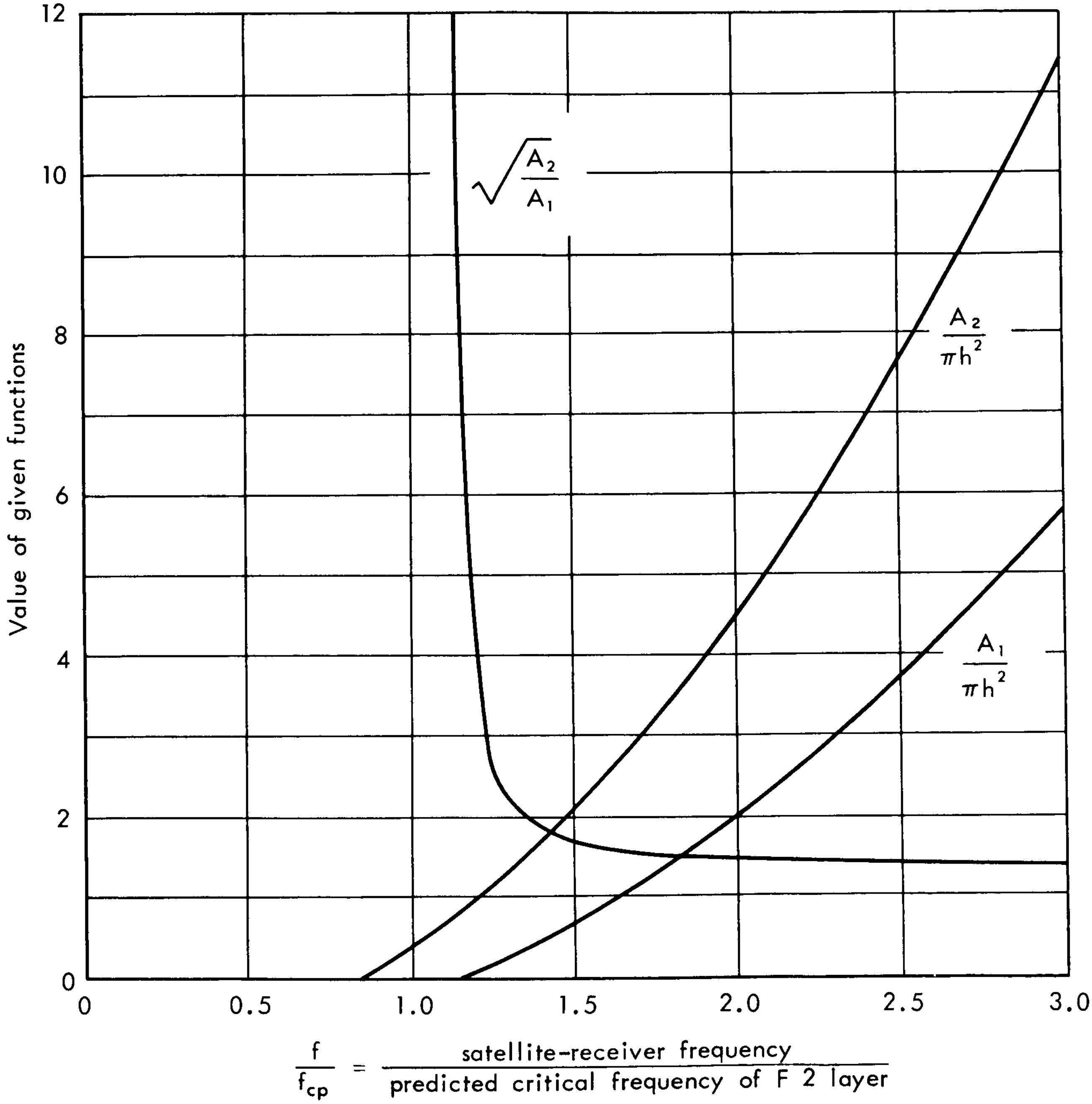

Fig. 2 Range of areas observed from a satellite
80% of the time as a function of satellite receiver frequency

frequency observed should be about 1.5 to 2 times the predicted critical frequency of the F2 layer at the point where the satellite is. If several frequencies are recorded in the satellite and the data are relayed to the earth, the frequency that best fits this criterion can be chosen and the thunderstorm density estimated on the ground without requiring appreciable data storage or computation in the satellite. This method of estimating the thunderstorm density is also subject to error because the signals coming from the edge of the circle of observation do not travel to the satellite in a straight line. The amount of this error could be estimated from a detailed analysis of paths followed by these signals as they traverse typical ionosphere electron distributions, but this will not be attempted here.

If greater accuracy is desired it will be necessary to limit the field of view by the use of a directional antenna. Although it may not be difficult to carry the required antenna on a satellite, the use of such an antenna will require that the satellite be oriented properly so that the antenna will be pointed downwards. This will add considerable complexity to the entire satellite system. If such a system is used, it will be desirable to observe at a much higher frequency than would be used if the ionosphere is to control the field of view, partly because directional antennas are smaller and lighter at higher frequencies, and partly because the use of a higher frequency will decrease any errors incurred from the fact that the path of propagation through the ionosphere is not a straight line. Since the intensity of the signal from a lightning stroke decreases with increasing frequency, the upper limit to the usable frequency will be determined by the signal-to-noise ratio in the receiver. For this reason the noise levels encountered by a receiver in a satellite will now be considered.

III. THE NOISE RECEIVED BY THE SATELLITE

The types of interfering signals that will affect a receiver on a satellite and compete with the signal from the lightning flash are mentioned in the Introduction. Some estimates of their intensities have been compiled in Ref. 4. It will be assumed here that it is possible to choose the observed frequency and bandwidth so that man-made signals will seldom be detected, or that such signals can be discriminated against because of their waveform, which does not usually have the impulsive nature of signals generated by thunderstorms. Thus the only interfering signals are receiver noise, noise of solar and cosmic origin, and noise produced by absorbing regions, primarily by thermal excitation of oxygen and water vapor in the atmosphere.

The receiver-noise power is roughly equal to kTB, where k is Boltzmann's constant, T the absolute temperature of the receiver, and B the bandwidth of the receiver. It is customary to assume that T is about $290^{\circ}K$. The actual temperature of a receiver in space may be considerably less than this, and the use of low-noise input circuits may further reduce the effective temperature to as little as half of this value without greatly increasing the complexity of the receiver. However, receiver noise generated at points after the input circuit tends to increase the total effective noise level to a value greater than that associated with the actual temperature of the receiver. It seems unlikely that all of these considerations will change the total effective receiver noise by much more than a factor of two. Since this is not enough to be very important in the present analysis, the receiver noise will be assumed to be kTB, where T is taken to be $290^{\circ}K$, and B will be taken to be 1000 cps. The use of a bandwidth this narrow will help to eliminate man-made interference. For these values of T and B the effective receiver noise at the input to the receiver is $4.0 \cdot 10^{-18}$ W.

Solar noise is thermal radiation from the sun and can also be approximated by the expression kTB if T is chosen to be the temperature of the part of the sun from which the radiation is being received. However, this estimate is only valid if the entire field of view of the antenna is filled with material radiating at this temperature. The satellite antenna considered here will either be nearly nondirectional or be a directional antenna that is aimed downward and receives signals from the sun only through backlobes whose maximum gain is not often more than the gain of an isotropic antenna. Thus for the accuracy needed here, the noise in the receiver will be less than the value kTB by a factor equal to the ratio of the solid angle filled by the sun to 4π, which is the total solid angle observed by a nearly isotropic antenna. The effective angular diameter of the sun depends on the frequency at which it is observed but is never much more than 1°. Using this angular diameter the solar noise received by the receiver is about $1.9 \cdot 10^{-5}$ kTB. The effective temperature of the sun at the frequencies of interest is about 10^6 degrees K, so the solar noise received by the receiver will be roughly the same as the internal noise that would be produced in the receiver if its input circuitry were at a temperature of about 19°K. Thus the solar noise is much less than the receiver noise, and the two together should be less than 10^{-17} W. This value is indicated in Fig. 3. The solar noise estimated here is for a quiet sun and may occasionally increase considerably if the sun is disturbed.

Cosmic noise data is also given in Ref. 4. Cosmic noise is strongest from the direction of the center of the galaxy, less intense from the disc of the galaxy, and least intense from the regions outside of the disc of the galaxy. When viewed with a nearly isotropic antenna or with the backlobes of a directional antenna, the total received noise will be about equal to the average noise arriving from all directions. Using the maps given in Ref. 4 showing cosmic noise intensities from different parts of the sky at different frequencies, estimates have been made of the average noise from all directions. It is found that since the disc of the galaxy occupies only a small part of the sky the average noise is greater than the minimum noise by a factor of only about 1.5 to 2. Since half of the sky is screened by the earth and is not visible, the

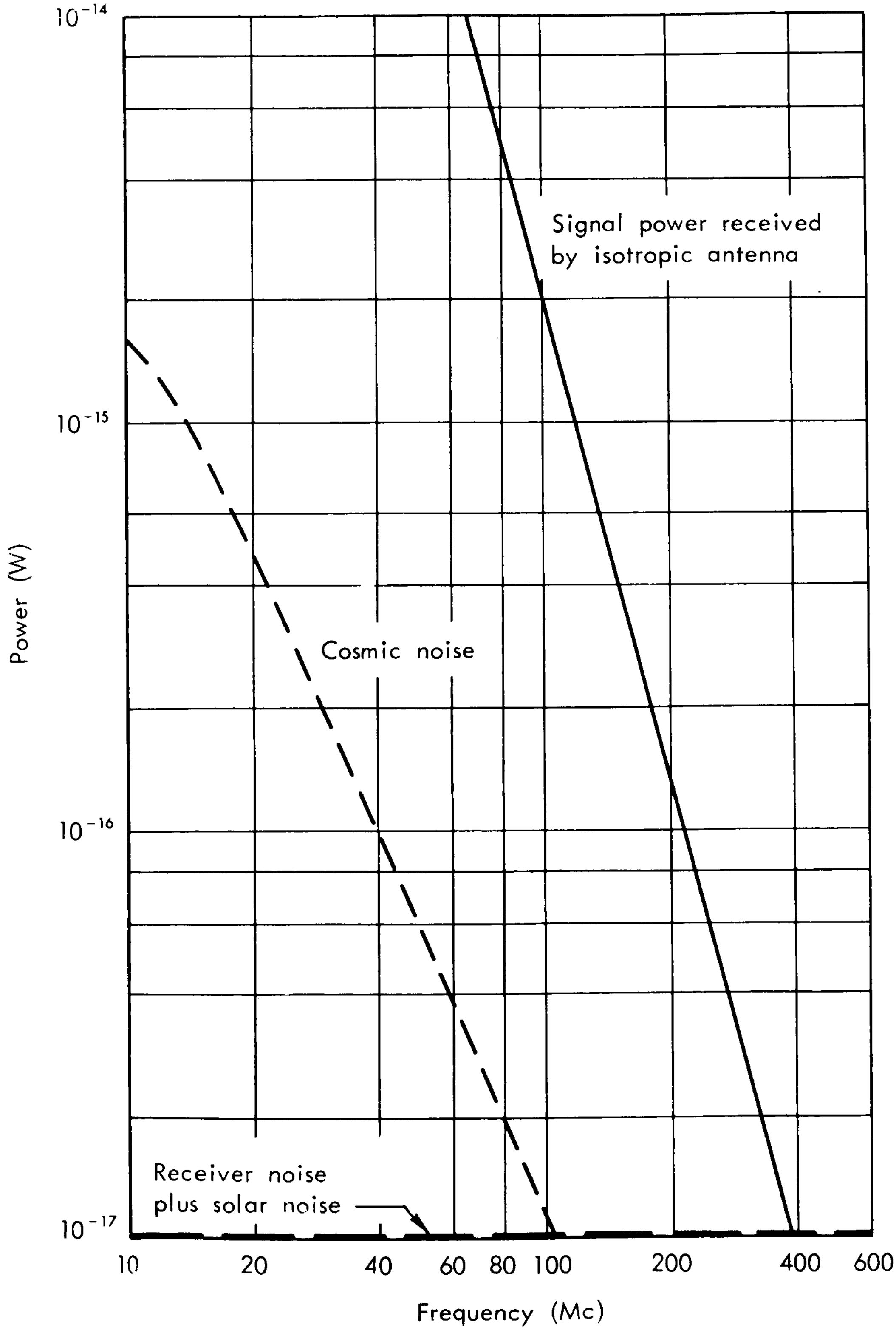

Fig. 3 Signal and noise in a one-kilocycle band

received noise will be less than the average noise by a factor of two. Combining these two factors shows that a reasonable estimate of the received noise is that it is roughly equal to the minimum noise received from any one direction. A curve of this minimum noise in a 1000-cycle bandwidth is plotted as a function of frequency in Ref. 4 and is reproduced in Fig. 3.

Noise produced by the oxygen and water vapor in the atmosphere has also been estimated in Ref. 4, and it is shown to be well below the receiver noise levels considered here at any frequency below 10,000 Mc. For this reason it will be ignored here.

The signal to be expected has been described in Section II. The field strength incident on the antenna is roughly 1/2 volt/meter in a 1 kc band at a center frequency of 100 kc and at a distance of 1 mile from the source. If the satellite altitude is about three or four hundred miles, the distance of the satellite from the source may be about five hundred miles, and the field strength at this distance will be less than that at 1 mile by a factor of 500 and so will be about 1 mv/m. The power delivered to the receiver is the square of the field strength divided by the characteristic impedance of space (120π ohms in mks units) and multiplied by the effective antenna aperture. The aperture of the antenna is $\lambda^2/4\pi$ times the gain of the antenna, where λ is the wavelength. At 100 kc, $\lambda = 3000$ m, so if the antenna is isotropic and has a gain of one, the receiver power in a 1 kc band will be about 1.9 mW. Since at frequencies above 100 kc the field strength is assumed to vary inversely with the frequency, and since wavelength also varies inversely with frequency, the received power will vary inversely as the fourth power of the frequency. Its actual value is shown in Fig. 3. If the receiving antenna has an appreciable gain in the direction of the thunderstorm, the received signal power is the value given in Fig. 3 multiplied by the gain of the antenna.

It is seen from Fig. 3 that cosmic noise will never be a limiting factor in reception and can usually be ignored, but that the average signal power will be greater than the receiver and solar noise only at frequencies below 400 Mc. The amplitudes of signals radiated from lightning strokes vary over a range of at least 10 to 1, so the weaker strokes will be detectable only if the average signal is at least three times the minimum detectable signal. Furthermore, for reliable detection of all strokes, the amplitude of the signal should be somewhat greater than that of the noise. Thus the average signal amplitude should be at least five times that of the noise, and the minimum acceptable power signal-to-noise ratio is about 25.

The actual signal will be greater than the one shown in Fig. 3 by the antenna gain. If the antenna had a uniform gain in all directions within the cone whose axis is vertical and whose half angle is 30° and had a gain of zero elsewhere, its gain within this cone would be about 15. Thus if an appreciable area below the satellite is to be studied the antenna gain will probably be about 10 or 20. The physical size of such an antenna will be about equal to its effective aperture if the antenna is a parabolic reflector fed at its focus or a broadside array with a flat reflector behind it. This effective aperture is $\lambda^2/4\pi$ times the gain, or roughly λ^2 for gains of the size considered above. If the system were to operate at 300 Mc, where the wavelength is one meter, the antenna area would be only about a square meter. An antenna composed of a flat square reflector one meter on a side with four half-wave doublet antennas in front of it would give roughly the desired result and could be light enough and compact enough to be practical on a satellite. If such an antenna had a gain of 10, it is seen from Fig. 3 that the average signal-to-noise ratio at 300 Mc would be about 25, which is an acceptable ratio on the basis of the discussion in the previous paragraph.

These results suggest that a satellite observing thunderstorms should use a frequency of about 300 Mc or less. If an extremely low-noise receiver were used, the effective noise temperature of the receiver might be reduced to as little as the value of $19^{\circ}K$ associated with solar noise. Then the combined receiver and solar noise might be reduced to a value of about $5 \cdot 10^{-19}$ W in a 1 kc bandwidth. This is less than the value of 10^{-17} W shown in Fig. 3 by a factor of 20. The maximum possible detection frequency then increases by a factor of $\sqrt[4]{20}$, or about 2. Thus the maximum usable frequency might be increased to six or seven hundred megacycles. Although this will decrease the dimensions of the antenna to half of their original values, it will appreciably increase the complexity of the receiver, since a maser amplifier would be needed. It is not clear that the over-all system would be simplified by such a change.

Increasing the detection frequency above about 300 Mc still further increases the uncertainty associated with the shape of the frequency spectrum of the incident field strength, which has been assumed to vary inversely with the frequency. Data given in Ref. 3 show a wide spread in the measured values of this spectrum, and the data are still too sparse to prove or disprove the assumption made here. More measurements of this spectrum should be made before any firm conclusions are drawn about the maximum allowable detection frequency. In the meantime, 300 Mc seems a not unreasonable value.

IV. THE POSSIBLE USE OF WHISTLER-MODE PROPAGATION

The analysis above is based on the use of the usual ionospheric propagation mode, which is the only mode that can exist in the absence of a magnetic field. As mentioned above, the presence of the magnetic field of the earth may modify the propagation characteristics of this mode, but the effect is not usually great enough to be significant. However, the presence of the magnetic field might still be important, because it makes possible another completely different mode of propagation usually called the whistler mode. Signals traveling by this mode can travel through the ionosphere at frequencies far below the critical frequency of the usual ionospheric mode. In fact, whistler-mode signals can often be detected by connecting the antenna directly to an audio amplifier and listening to the note produced at audible frequencies. In whistler-mode propagation the higher frequencies usually travel more rapidly than the lower ones with the result that the high-frequency components from a remote lightning flash are received before the lower-frequency components, and the audible note is a descending whistle, giving rise to the name of the whistler mode. In the whistler mode signals can propagate only at frequencies that are lower than both the plasma frequency and the gyro-frequency of electrons in the magnetic field. Thus whistler-mode signals cannot penetrate the ionosphere at frequencies above the critical frequency of the ionosphere and, therefore, cannot give rise to any signals that might interfere with signals propagated through the ionosphere by the usual ionospheric mode. However, if the satellite detects frequencies less than the critical frequency and also less than the gyro-frequency (which varies from about 0.8 to 2 Mc at the surface of the earth), it could detect thunderstorms by use of whistler-mode propagation.

For the present purposes one of the most important features of whistler-mode propagation is that the signal tends to travel along the direction of the magnetic field. This occurs because the criterion that determines whether or not a signal will propagate along a given path depends upon the angle between the direction of propagation and the magnetic field as well as upon the electron density. Propagation is possible only if this angle is less than some maximum value. When the frequency is much less than the gyro-frequency (and the effect of positive ions is neglected) propagation will occur only if the angle between the ray and the magnetic field is less than about 20°. At successively higher frequencies, the maximum allowable value of this angle is lower, having a value of about 11° when the frequency is about 20% of the gyro-frequency. At still higher frequencies the maximum value of this angle is again progressively higher, and at frequencies close to the gyro-frequency, all directions of the ray are possible. At frequencies above the gyro-frequency whistler-mode propagation is not possible. At very low frequencies, of the order of 1000 cycles/sec or less, the frequency may be of the same order as the gyro-frequency of the positive ions, and these may affect the propagation characteristics. Here again all directions of propagation become possible.

The results just outlined hold for a homogeneous electron distribution. However, since charged particles in a magnetic field tend to spiral along the field lines, the electron distribution is more likely to be nearly homogeneous along the field lines than it is in directions perpendicular to the magnetic field. Inhomogeneities aligned with the magnetic field tend to act as ducts that will confine the field by total internal reflection. This effect further increases the tendency of whistler-mode signals to travel along the magnetic field.

As a result of this tendency, a signal received by a satellite at a frequency that lies in the band in which whistler propagation is possible will usually have come from one of the two areas on the earth at which the magnetic field line through the satellite intersects the surface of the earth. This means that signals from the equatorial regions, where thunderstorm activity is the greatest, may often be impossible to detect from a satellite. If the frequency observed is very low (of the order of 1000 cycles/sec or less) or is nearly equal to the electron gyro-frequency, the path of the signal is less likely to follow the magnetic field lines, and signals from equatorial sources may be more easily detectable. However, even in this situation, the source might be located anywhere in a very wide area, and a directional antenna is still desirable to determine its location more exactly. When the source is not near the Equator, the signal can be detected by whistler-mode propagation that follows the magnetic field lines, but it will not always be possible to determine whether the source is in the Northern or the Southern Hemisphere unless a properly oriented directional antenna is used on the satellite. Any frequency at which whistler-mode propagation can occur will be less than the maximum electron gyro-frequency of about 2 Mc, so that the wavelength associated with such a frequency will be 150 meters or more. At these wavelengths, even a moderately directional antenna would have a dimension of at least 150 meters in each direction. Such an antenna seems completely unreasonable for any satellite that might be available in the near future. For this reason the use of whistler-mode propagation for observing thunderstorm activity from a satellite will not be discussed further.

V. CONCLUSIONS

It is concluded that it should not be difficult to estimate the amount of thunderstorm activity by measuring the radio-frequency radiation from strokes of lightning with equipment located on a satellite. The best frequencies for detecting these signals appear to be either in the range of about 1.5 to 2 times the critical frequency of the F2 layer (an operating frequency in the range of about 6 to 20 Mc) or at a higher frequency of about 300 Mc.

For operation at a frequency of 1.5 to 2 times the F2 critical frequency, it seems reasonable that several different frequencies in the range of 6 to 20 Mc should be detected by the satellite's receiver. The observed data would be relayed to the ground, where the frequency that comes closest to desired range of about 1.5 to 2 times the predicted F2 critical frequency at the point of observation would be used to estimate the thunderstorm activity. In this way the ionosphere itself can be used to limit the field of observation with the result that a very simple antenna can be used on the satellite, and the orientation of the satellite need not be controlled. The disadvantage of this system is that the accuracy of the result depends on the accuracy with which the properties of the ionosphere can be estimated. Thus the result may sometimes be in error by a factor of as much as 2. This error may not always be important, but it must be considered.

For operation at the higher frequency of about 300 Mc the satellite should use a directional antenna and must then be properly oriented so that the antenna is pointed downward, which will increase the complexity of the system. On the other hand the resulting estimates of thunderstorm activity will be essentially independent of any knowledge about the ionosphere and for this reason should be a little more reliable than the estimates made at lower frequencies. The feasibility of making such estimates at this frequency depends upon the frequency spectrum of a lightning stroke up to frequencies of several hundred megacycles. This should be further investigated experimentally. Additional data might appreciably decrease the maximum desirable operating frequency.

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